New Results from MiniBooNE:

A search for $\bar{\nu}_e$ appearance at $\Delta m^2 \sim 1 \text{ eV}^2$

Georgia Karagiorgi, MIT
Results and Perspectives in Particle Physics
Les 23$^{rd}$ Rencontres de Physique de la Vallée d'Aoste

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March 1-7, 2008
Another $\Delta m^2$?

LSND experiment:

- Detected anti-$\nu_e$ from stopped pion source: $\pi^+ \rightarrow \mu^+ \rightarrow \bar{\nu}_\mu$

  Observed excess: $87.9 \pm 22.4 \pm 6.0$ anti-$\nu_e$ events (3.8σ)

  [arXiv:hep-ex/0104049]

Possible interpretation:

2-neutrino mixing with:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 (2\theta) \sin^2 \left( \frac{1.27 L \Delta m^2}{E} \right) = 0.245 \pm 0.067 \pm 0.045 \%$$

Best fit: $\sin^2(2\theta) = 0.003$, $\Delta m^2 = 1.2 \text{ eV}^2$
Why not?

Only 2 independent $\Delta m^2$:

3-neutrino mixing scheme established by atmospheric and solar experiments cannot accommodate for the LSND oscillation interpretation
The MiniBooNE Experiment:

Designed to test: \[ P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta) \sin^2 \left( \frac{1.27 L}{E} \Delta m^2 \right) \approx 0.25 \% \]

800 ton mineral oil Cherenkov detector
12 m in diameter (450 ton fiducial volume)
lined with 1280 inner PMT’s, and 240 outer veto PMT’s

Requirement: Place detector to preserve LSND L/E \[ \rightarrow \]
MiniBooNE: 500 m / 800 MeV
LSND: 30 m / 50 MeV \[ \text{[Different detection method and systematics]} \]
The MiniBooNE Experiment:

Event signatures:
Looking for $\nu_e$ signal in $\nu_\mu$ dominated beam...

Signal
$\nu_e$ charged-current quasi-elastic events
$$\nu_e + n \rightarrow e^- + p$$

Dominant type of interaction
$\nu_\mu$ charged-current quasi-elastic events
$$\nu_\mu + n \rightarrow \mu^- + p$$
The analysis...

A **blind** analysis chain was implemented...


**Track-based analysis (TBA)**
*[but also boosted-decision-tree (BDT) analysis]*

<table>
<thead>
<tr>
<th>Beam Flux Prediction</th>
<th>Cross Section Model</th>
<th>Optical Model</th>
<th>Event Reconstruction</th>
<th>Particle Identification</th>
<th>Simultaneous Fit to $\nu_\mu$ and $\nu_e$ events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start with a Geant 4 flux prediction for the $\nu$ spectrum from $\pi$ and $K$ produced at the target</td>
<td>Predict $\nu$ interactions using the Nuance event generator</td>
<td>Pass final state particles to Geant 3 to model particle and light propagation in the tank</td>
<td>Use track-based event reconstruction</td>
<td>Use hit topology and timing to identify electron-like or muon-like Cherenkov rings and corresponding charged current neutrino interactions</td>
<td>Fit reconstructed energy spectrum for oscillations</td>
</tr>
</tbody>
</table>

03/03/2009
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A glimpse of hope...

MiniBooNE has searched for $\nu_\mu \rightarrow \nu_e$ oscillations at $\Delta m^2 \sim 1 \text{ eV}^2$

Observed no excess consistent with the LSND two-neutrino oscillation...

...and therefore ruled out LSND $\nu_\mu \rightarrow \nu_e$ oscillation interpretation:

Assumptions:
2-v oscillation, with standard L/E dependence
$\rightarrow$ no CP or CPT violation

But another mystery…

But observed **unexpected excess** of events at low energy…


Interpretations include:

- CP violation with 2 sterile $\nu$
  

- Extra dimensions
  
  [Pas, Pakvasa, Weiler, hep-th/0701058]

- New particles
  
  [Nelson, Wall, hep-ex/0612124]

- CPT/Lorentz violation
  
  [Katori, Kostelecky, Tayloe, PRD 74, 105009 (2006)]

- New interactions
  
  [Harvey, Hill, Hill, hep-ph/0708.1281]

- VSBL $\nu_e$ disappearance
  
  [Giunti, Laveder, PRD 77, 093002 (2008)]

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**low energy excess region**

128.8 ± 43.4 excess events (3.0σ)

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Addressing the MiniBooNE and LSND anomalies

Through antineutrino running @ MiniBooNE: $\bar{\nu}_e$ appearance search

First antineutrino results (this talk), for 3.4e20 protons on target (POT)!
(new results coming soon, for 5.0e20 POT)

How do we get $\bar{\nu}_e$?

by switching horn polarity, we focus negatively charged mesons, yielding an anti-$\nu_\mu$ beam

Antineutrino dataset is used to address both CP/CPT violating $\nu_\mu \rightarrow \nu_e$ oscillations, and MiniBooNE low energy excess interpretations
Looking for $\bar{\nu}_e$ signal…

Background composition for $\bar{\nu}_e$ appearance search (3.4e20 POT):

<table>
<thead>
<tr>
<th>$N_{\text{events}}$</th>
<th>200-475 MeV</th>
<th>475-1250 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>intrinsic $\bar{\nu}_e$</td>
<td>17.7</td>
<td>43.2</td>
</tr>
<tr>
<td>from $\pi^{\pm}/\mu^{\pm}$</td>
<td>8.4</td>
<td>17.1</td>
</tr>
<tr>
<td>from $K^{\pm}, K^0$</td>
<td>8.2</td>
<td>24.9</td>
</tr>
<tr>
<td>other $\bar{\nu}_e$</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>mis-id $\nu_\mu$</td>
<td>42.5</td>
<td>14.6</td>
</tr>
<tr>
<td>CCQE</td>
<td>2.9</td>
<td>1.2</td>
</tr>
<tr>
<td>NC $\pi^0$</td>
<td>24.6</td>
<td>7.2</td>
</tr>
<tr>
<td>$\Delta$ radiative</td>
<td>6.6</td>
<td>2.0</td>
</tr>
<tr>
<td>dirt</td>
<td>4.7</td>
<td>1.9</td>
</tr>
<tr>
<td>other $\nu_\mu$</td>
<td>3.8</td>
<td>2.2</td>
</tr>
<tr>
<td>Total bkgd</td>
<td>60.3</td>
<td>57.8</td>
</tr>
<tr>
<td>LSND best fit</td>
<td>4.3</td>
<td>12.6</td>
</tr>
</tbody>
</table>

(only anti-$\nu_\mu$ assumed to oscillate)

[Graph showing background composition with LSND best fit $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ ($\Delta m^2, \sin^2 2\theta$) = (1.2, 0.003)]

[Note: statistical-only errors shown]
Dominant background (at low energy)
$\bar{\nu}_\mu$ neutral-current interactions with photon(s)
in the final state

For example, NC $\pi^0$:
$\bar{\nu}_\mu + n/p \rightarrow n/p + \pi^0 + \bar{\nu}_\mu$

$\pi^0 \rightarrow \gamma\gamma$

…“$\gamma$” looks like “$e$” in a Cherenkov detector

[diagram showing $\gamma$ (shower)]

[graph showing event yields with LSND best-fit $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$]

[note: statistical-only errors shown]
MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ sensitivity (3.4e20 POT)

KARMEN: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search
Compatibility with LSND at 64% CL

Do $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$?

$\bar{\nu}_e$ data vs. background distribution (3.4e20 POT):

$\chi^2_{null} (dof) = 24.5 \pm 19$
$\chi^2$-probability = 17.7%

$\chi^2_{best-fit} (dof) = 18.2 \pm 17$
$\chi^2$-probability = 37.8%

MiniBooNE best-fit:
$(\Delta m^2, \sin^22\theta) = (4.4 \text{ eV}^2, 0.004)$

No significant excess observed at both low and high energy!
Do $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$?

With $3.4 \times 10^{20}$ POT, MiniBooNE places a limit to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations:

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**KARMEN:**

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search

- 90% CL
- 3σ CL
- 5σ CL
- BDT, 90% CL

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### What about the low energy excess?

<table>
<thead>
<tr>
<th>$E_v^{QE}$ range (MeV)</th>
<th>$\bar{v}$ mode (3.4e20 POT)</th>
<th>$v$ mode (6.5e20 POT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(same binning as in neutrino mode)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200-475</td>
<td>Data</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>$MC \pm$ sys+stat (constr.)</td>
<td>61.5 ± 11.7</td>
</tr>
<tr>
<td></td>
<td>$Excess (\sigma)$</td>
<td>-0.5 ± 11.7 (-0.04)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>415.2 ± 43.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>128.8 ± 43.4 (3.0)</td>
</tr>
<tr>
<td>475-1250</td>
<td>Data</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>$MC \pm$ sys+stat (constr.)</td>
<td>57.8 ± 10.0</td>
</tr>
<tr>
<td></td>
<td>$Excess (\sigma)$</td>
<td>3.2 ± 10.0 (0.3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>385.9 ± 35.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>22.1 ± 35.7 (0.6)</td>
</tr>
</tbody>
</table>

How consistent are excesses in neutrino and antineutrino mode under different underlying hypotheses as the source of the low energy excess in neutrino mode?

**Possibilities:**

- **Background & New Physics**

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What about the low energy excess?

**Suggested hypotheses:**

Include processes contributing either a single-electron or a single-gamma.

**“New” physics? E.g.**

Anomaly-mediated photon production?

Assumed to contribute equally for neutrinos and antineutrinos.

[Harvey, Hill, and Hill, hep-ph0708.1281]

Standard Model, but odd...
What about the low energy excess?

*Suggested hypotheses:*

Include processes contributing either a single-electron or a single-gamma

Or background? E.g.

- Misestimated $\pi^0$?

  To account for $\nu$ mode excess, $\pi^0$ background would have to be misestimated by a factor of 2...

  Unlikely, since the $\pi^0$ rate is measured to 5%.


$\pi^0$: most dominant background at low energy
**What about the low energy excess?**

In testing these hypotheses, the excess is assumed to scale from neutrinos to antineutrinos as follows:

- The same $\nu, \bar{\nu}$ NC cross section (e.g. HHH axial anomaly [hep-ph/0708.1281])
- The same cross section ratio as NC $\pi^0$ background (cross section is different for $\nu, \bar{\nu}$)
- With POT (e.g. K0L-induced events)
- With Background
- CC cross section ratio
- Low-E Kaons
- Neutrinos only (no antineutrinos) (neutrino induced interaction)

Flux and protons on target (POT) in neutrino and antineutrino mode were taken into account in the scaling.
What about the low energy excess?

**Maximum $\chi^2$ probability from fits to $\nu$ and $\bar{\nu}$ excesses in 200-475 MeV range**

<table>
<thead>
<tr>
<th></th>
<th>Stat Only</th>
<th>Correlated Syst</th>
<th>Uncorrelated Syst</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same $\nu,\bar{\nu}$ NC</td>
<td>0.1%</td>
<td>0.1%</td>
<td>6.7%</td>
</tr>
<tr>
<td>NC $\pi^0$ scaled</td>
<td>3.6%</td>
<td>6.4%</td>
<td>21.5%</td>
</tr>
<tr>
<td>POT scaled</td>
<td>0.0%</td>
<td>0.0%</td>
<td>1.8%</td>
</tr>
<tr>
<td>Bkgd scaled</td>
<td>2.7%</td>
<td>4.7%</td>
<td>19.2%</td>
</tr>
<tr>
<td>CC scaled</td>
<td>2.9%</td>
<td>5.2%</td>
<td>19.9%</td>
</tr>
<tr>
<td>Low-E Kaons</td>
<td>0.1%</td>
<td>0.1%</td>
<td>5.9%</td>
</tr>
<tr>
<td>$\nu$ scaled</td>
<td>38.4%</td>
<td>51.4%</td>
<td>58.0%</td>
</tr>
</tbody>
</table>

(“lower limit”) ("upper limit")

- Same $\nu$ and $\bar{\nu}$ NC cross-section (HHH axial anomaly), POT scaled, Low-E Kaon scaled: disfavored as an explanation of the MiniBooNE low energy excess!

- The most preferred model is that where the low-energy excess comes from neutrinos in the beam (no contribution from anti-neutrinos).
Current status & prospects:

We have performed a blind analysis to \( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \) oscillations:
\( \bar{\nu}_e \) data in agreement with MonteCarlo background prediction as a function of \( E_\nu^{QE} \).

So far, **no strong evidence for oscillations in antineutrino mode** (although currently limited by statistics).

Interestingly, **no evidence of significant excess at low energy** in antineutrino mode. This has already placed constraints to various suggested low energy excess interpretations.

In process of **collecting more data** for a total of 5.0e20 POT. This will improve sensitivity to oscillations, and allow further investigation of the \( \nu \) low energy excess. Have submitted a request for 10.0e20 POT.
Combined $\nu_e$ and $\bar{\nu}_e$ analysis for low energy events with systematic correlations properly included, for testing various low energy excess interpretations

Combined $\nu_e$ and $\bar{\nu}_e$ appearance analysis (with CP violation) for stronger constraints on oscillations

Combined MiniBooNE-NuMI $\nu_e$ appearance analysis

NuMI $\nu_e$ distribution [uses different beam]

Thank you!

The MiniBooNE Collaboration

03/03/2009

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The LSND experiment

LSND looked for $\bar{\nu}_e$ appearing in a $\bar{\nu}_\mu$ beam

Signature:
- Cerenkov light from $e^+$ (CC)
- Scintillation light from nuclear recoil
- Delayed n-capture (2.2 MeV)
MiniBooNE antineutrino running

MiniBooNE antineutrino flux prediction:

Event rates:
(xsec-weighted, after selection cuts)

~14,000 $\bar{\nu}_\mu$ CCQE events
(~70% pure)

~ 140 $\bar{\nu}_e$ CCQE events
(~40% pure)

First antineutrino results correspond to
dataset collected for 3.4e20 POT

[arXiv:0806.1449 [hep-ex], accepted by Phys. Rev. D]
MiniBooNE flux prediction

neutrino mode: $\nu_\mu \rightarrow \nu_e$ oscillation search

antineutrino mode: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation search

WS further amplified to ~30% in $\bar{\nu}$ mode due to cross-section

$\sim 6\% \bar{\nu}$

$\sim 18\% \nu$
MiniBooNE event rate prediction

<table>
<thead>
<tr>
<th>( \nu ) channel</th>
<th>events</th>
<th>( \bar{\nu} ) channel</th>
<th>events</th>
</tr>
</thead>
<tbody>
<tr>
<td>all channels</td>
<td>895k</td>
<td>all channels</td>
<td>83k</td>
</tr>
<tr>
<td>CC quasielastic</td>
<td>375k</td>
<td>CC quasielastic</td>
<td>37k</td>
</tr>
<tr>
<td>NC elastic</td>
<td>165k</td>
<td>NC elastic</td>
<td>16k</td>
</tr>
<tr>
<td>CC ( \pi^+ )</td>
<td>200k</td>
<td>CC ( \pi^- )</td>
<td>14k</td>
</tr>
<tr>
<td>CC ( \pi^0 )</td>
<td>33k</td>
<td>CC ( \pi^0 )</td>
<td>2.6k</td>
</tr>
<tr>
<td>NC ( \pi^0 )</td>
<td>53k</td>
<td>NC ( \pi^0 )</td>
<td>7.6k</td>
</tr>
<tr>
<td>NC ( \pi^\pm )</td>
<td>30k</td>
<td>NC ( \pi^\pm )</td>
<td>2.8k</td>
</tr>
<tr>
<td>CC/NC DIS, multi-( \pi )</td>
<td>39k</td>
<td>CC/NC DIS, multi-( \pi )</td>
<td>2.9k</td>
</tr>
</tbody>
</table>

6.6\( \times 10^{20} \) POT  \\ \( \nu \) mode  \\
3.4\( \times 10^{20} \) POT  \\ \( \bar{\nu} \) mode

Although delivered POT only reduced by a factor of \(~2\), overall rate down by almost an order of magnitude!
Neutrino cross sections

Channel of interest at MiniBooNE: CCQE
**MiniBooNE systematics:**

Background systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>( E_{\nu}^{QE} ) range (MeV)</th>
<th>uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200-475</td>
<td>475-1100</td>
</tr>
<tr>
<td>Flux from ( \pi^+/\mu^+ ) decay</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>Flux from ( \pi^-/\mu^- ) decay</td>
<td>3.3</td>
<td>2.2</td>
</tr>
<tr>
<td>Flux from ( K^+ ) decay</td>
<td>2.3</td>
<td>4.9</td>
</tr>
<tr>
<td>Flux from ( K^- ) decay</td>
<td>0.5</td>
<td>1.1</td>
</tr>
<tr>
<td>Flux from ( K^0 ) decay</td>
<td>1.5</td>
<td>5.7</td>
</tr>
<tr>
<td>Target and beam models</td>
<td>1.9</td>
<td>3.0</td>
</tr>
<tr>
<td>( \nu ) cross section</td>
<td>6.4</td>
<td>12.9</td>
</tr>
<tr>
<td>NC ( \pi^0 ) yield</td>
<td>1.7</td>
<td>1.6</td>
</tr>
<tr>
<td>Hadronic interactions</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>External interactions (dirt)</td>
<td>2.4</td>
<td>1.2</td>
</tr>
<tr>
<td>Optical model</td>
<td>9.8</td>
<td>2.8</td>
</tr>
<tr>
<td>Electronics &amp; DAQ model</td>
<td>9.7</td>
<td>3.0</td>
</tr>
<tr>
<td><strong>Total (unconstrained)</strong></td>
<td><strong>16.3</strong></td>
<td><strong>16.2</strong></td>
</tr>
</tbody>
</table>

ANTINEUTRINO APPEARANCE SEARCH IS STATISTICS LIMITED
# Antineutrino results

## Background systematic uncertainties

<table>
<thead>
<tr>
<th>$E_{\nu}^{QE}$ fit</th>
<th>$\chi^2_{\text{null}}(\text{dof})$ $\chi^2$-prob</th>
<th>$\chi^2_{\text{null}}(\text{dof})^*$ $\chi^2$-prob</th>
<th>$\chi^2_{\text{best-fit}}(\text{dof})^*$ $\chi^2$-prob</th>
<th>$\chi^2_{\text{LSND best-fit}}(\text{dof})$ $\chi^2$-prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 200 MeV</td>
<td>24.51(19) 17.7%</td>
<td>20.18(17) 26.5%</td>
<td>18.18(17) 37.8%</td>
<td>20.14(19) 38.6%</td>
</tr>
<tr>
<td>&gt; 475 MeV</td>
<td>22.19(16) 13.7%</td>
<td>17.88(14) 21.2%</td>
<td>15.91(14) 31.9%</td>
<td>17.63(16) 34.6%</td>
</tr>
</tbody>
</table>

(*Covariance matrix approximated to be the same everywhere by its value at best fit point*)
### Antineutrino results

**$E_{\nu}^{QE}$ range (MeV)**  
(same binning as in neutrino mode)  

<table>
<thead>
<tr>
<th>$\bar{\nu}$ mode</th>
<th>$\nu$ mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>(3.4e20 POT)</td>
<td>(6.5e20 POT)</td>
</tr>
</tbody>
</table>

| $200-475$ | Data       | 61          | 544          |
| MC ± sys+stat (constr.) | 61.5 ± 11.7 | 415.2 ± 43.4 |
| Excess ($\sigma$) | -0.5 ± 11.7 ($-0.04$) | 128.8 ± 43.4 (3.0) |

- Performed 2-bin $\chi^2$ test for each assumption
- Calculated $\chi^2$ probability assuming 1 dof

\[
\chi^2 = \sum_{i,j}(D_i - (B_i + S_j))M_{ij}^{-1}(D_j - (B_j + S_j))
\]

$i, j = \nu, \bar{\nu} \ 200-475\text{MeV bin}$

The underlying signal for each hypothesis, $S$, was allowed to vary (thus accounting for the possibility that the observed signal in neutrino mode was a fluctuation up, and the observed signal in antineutrino mode was a fluctuation down), and an absolute $\chi^2$ minimum was found.

- Three extreme fit scenarios were considered:
  - Statistical-only uncertainties
  - Statistical + fully-correlated systematics
  - Statistical + fully-uncorrelated systematics
Low E interpretations

New light gauge boson


- 3 sterile neutrinos + gauged B-L interaction
- gives rise to MSW-type potential \(\rightarrow\) strong energy dependence in SBL, small mixing oscillations

Predicts higher anti-\(\nu\) than \(\nu\) oscillation probability
Low E interpretations

CP violation

\[ P(\nu^- \mu^- \nu^e) = 4|U_{\mu 4}|^2|U_{e 4}|^2 \sin^2 \theta_{41} + 4|U_{\mu 5}|^2|U_{e 5}|^2 \sin^2 \theta_{51} + 8 |U_{\mu 5}| |U_{e 5}| |U_{\mu 4}| |U_{e 4}| \sin \theta_{41} \sin \theta_{51} \cos (\theta_{45} \pm \phi_{45}) \]

\[ 3+2 \text{ sterile neutrino model oscillation probability} \]

Dirac CPV phase